Materials Needs For Advanced Navy Systems

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Future RF System Trends

- Fewer system types- rely on multi-functionality
- Reduced manpower
- Open architecture - upgradable, reconfigurable
- Low Radar Cross Section(RCS)
- Increased emphasis on small platforms, i.e. Micro-Air-Vehicles(MAVs), satellites, man-packs
- Balance of performance, risk and affordability

Technology Drivers for Emerging Systems

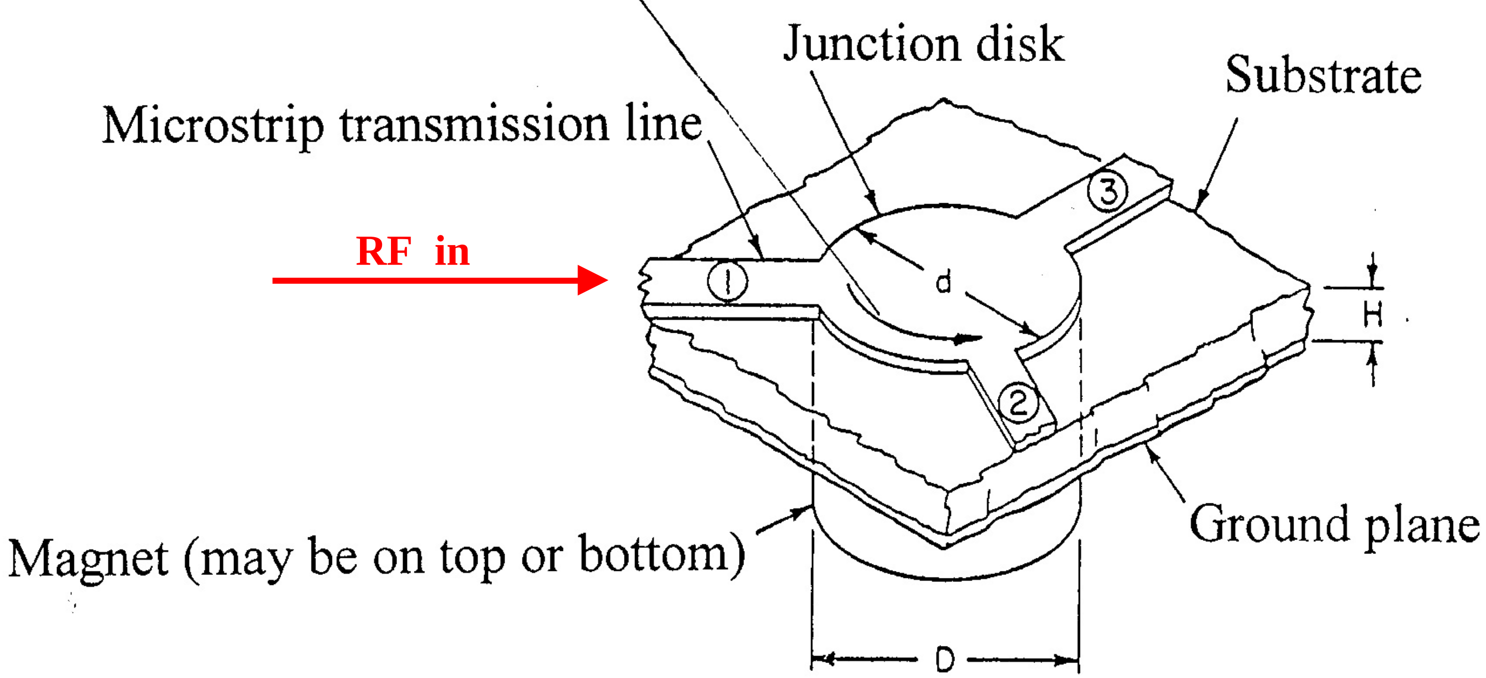
- High functionality per unit volume, miniaturization
- High efficiency, reduced cooling
- Increased signal throughput
- Wide instantaneous bandwidth
- High dynamic range, high isolation
- Low cost with minimal compromise in performance

RF Device Candidates for Meta-Materials

- Circulators and Isolators
- Phase shifters
- Filters

Microwave Microstrip Circulator

RF energy entering any port (1, 2, or 3) propagates through the junction in a counter clockwise direction exiting at the next available port.



Circulators and Isolators

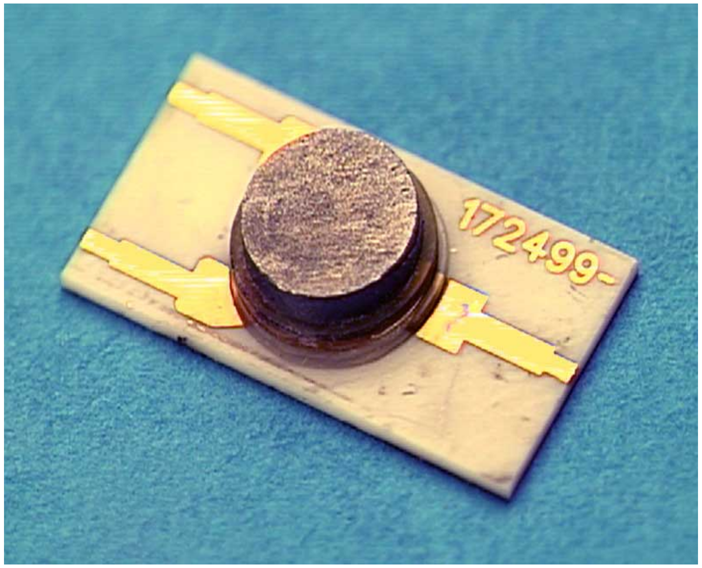
Problems/Limitations of Present Technology

- **Percentage bandwidth limited to 100%(F_{max}/F_{min} = 3)**
- **Footprint size, especially for 4+ port configurations**
- **Size/weight of permanent magnet bias**
- **Reproducibility**
- **Cost**

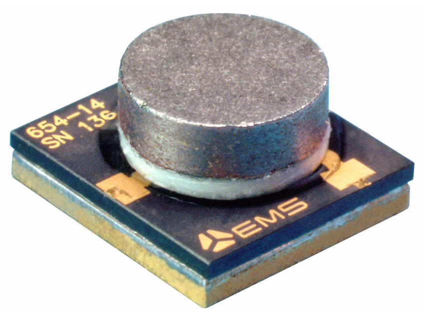
Circulator Size Reduction Approaches

- Lumped element designs
- Higher dielectric constants
- Internally - biased geometries

Microstrip Circulators



Baseline Design
0.500” x 0.500”
(not including 50 ohm lines)



Quasi-Lumped Element (QLEC) Circulator
0.240” x 0.250”

Courtesy of Electromagnetic Sciences, Inc

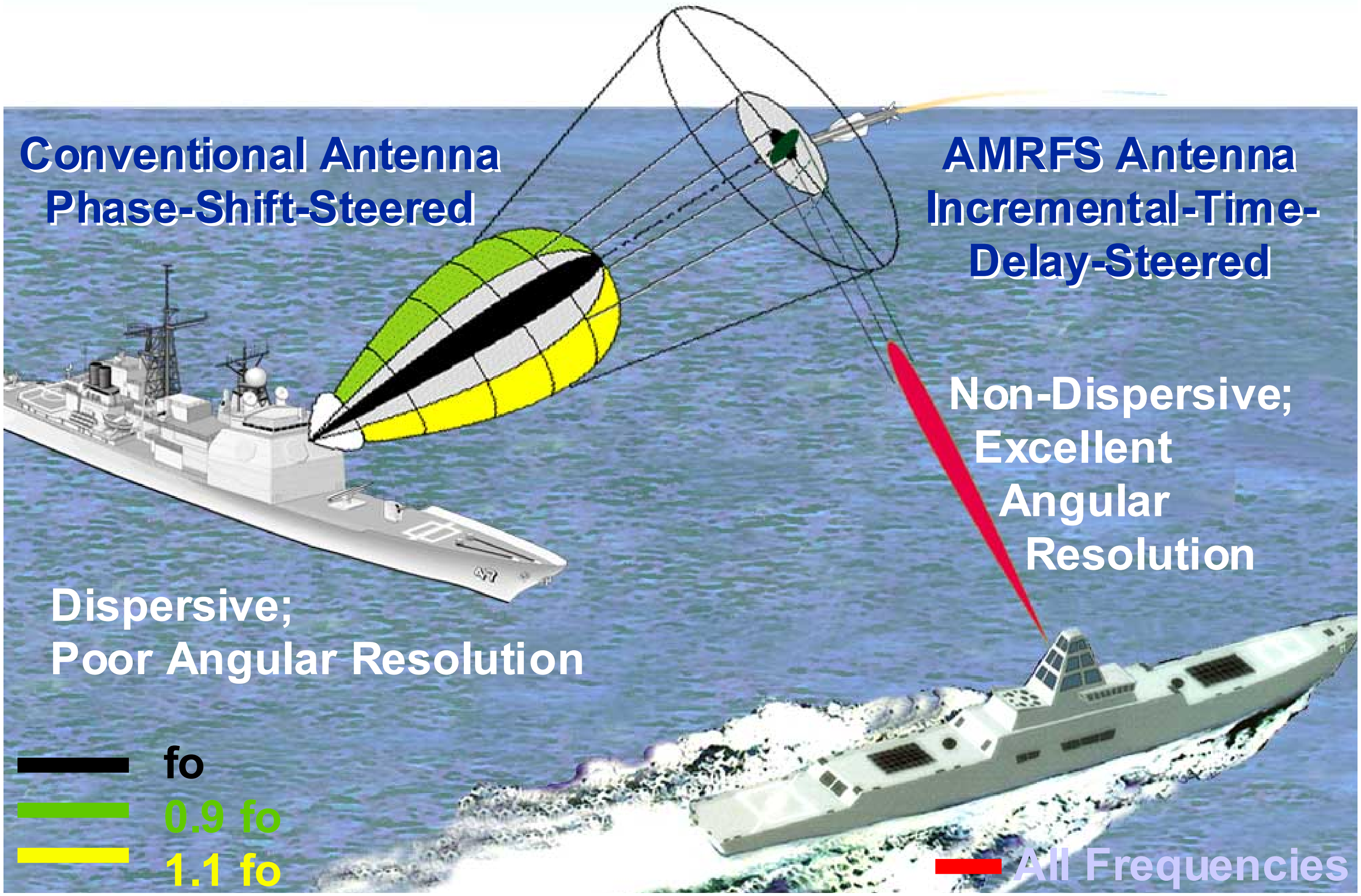
Phase Shifters

Requirements for Emerging Applications

- Real time delay
- Low loss
- High speed
- Low power consumption
- Low cost

Advanced Multifunction RF (AMRF) Concept

Large Time Bandwidth Product Signals



Planar Phase Shifter Loss
(360^{o} at 10 GHz)

•GaAs Analog	8.5 dB
•GaAs Digital*	8 dB
•Ferroelectric	5 to 6 dB
•Ferrite	1.5 dB
•MEMS*	1.15 dB

*4-bits

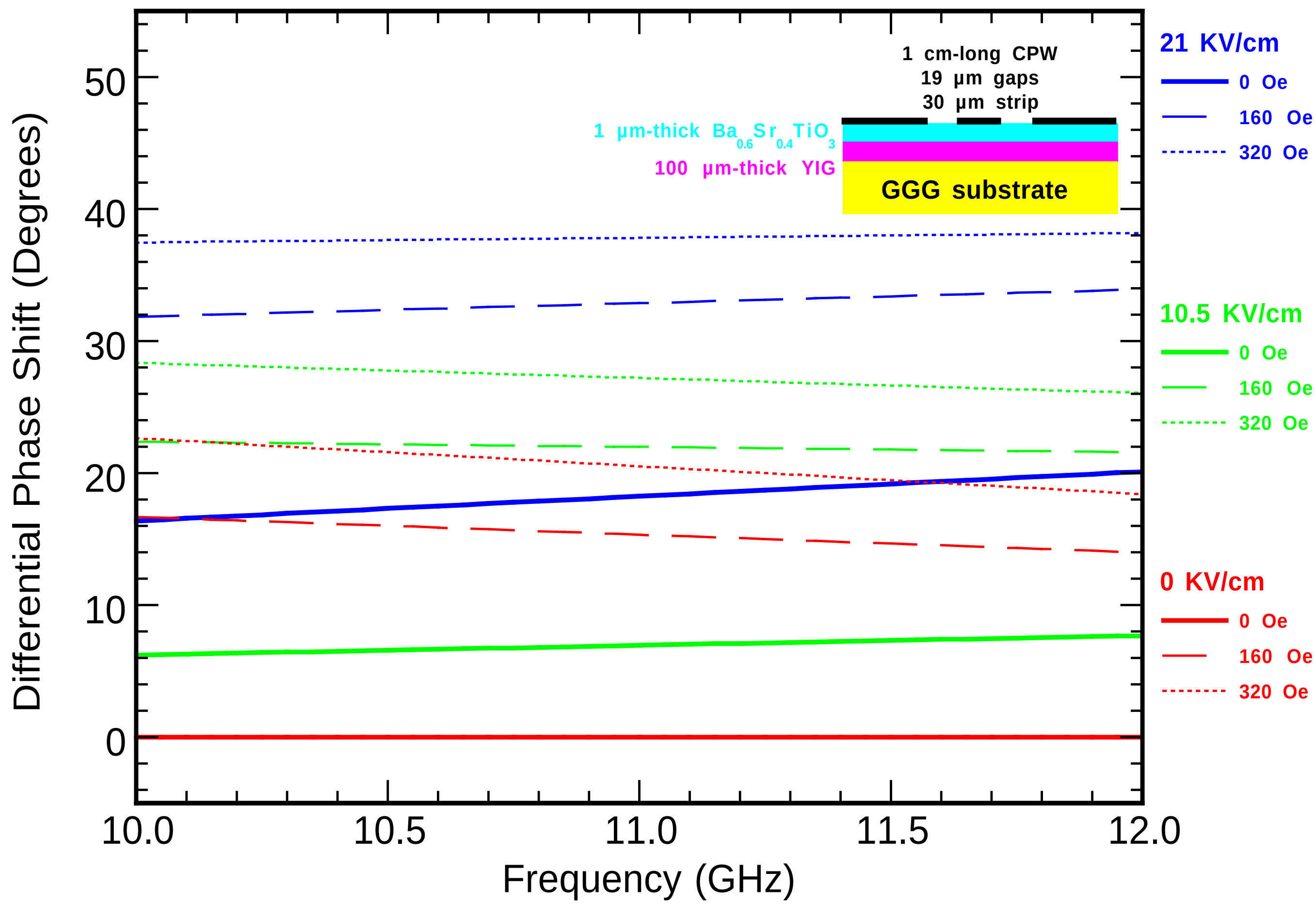
Typical MMIC Phase Shifter Performance* for Active Sub-Array

Phase Control	**0° or 180° (1 bit)**
Time Delay Control	**5 bit digital** **3 psec LSB; 48psec MSB** **(93 psec total)**
Time Delay Accuracy	**+/- 1.5 psec**
Total Phase Shift	**0 to 390° @ 6 GHz** **0 to 810° @ 18 GHz**
RF Power	**40 mw**
VSWR	**2.0:1 Max**
Size	**10mm x 8 mm**

***** ITT Avionics, MAFET Thrust 2

Ferrite - Ferroelectric Composite Phase Shifter

Electric Field and Magnetic Field Tuning of the Phase Velocity of a Coplanar Waveguide Transmission Line



Filters

Requirements for Emerging Applications

- Small Size
- High Q (low loss/high selectivity)
- Temperature Stable
- High Linearity
- High Power Handling
- Tunable

Miniature filters

- Need for small high-Q filters is greatly expanding
  - commercial wireless
  - high dynamic range receivers for DoD
- Approaches to high Q and small size
  - bulk-acoustic-wave
  - active (GaAs FET/MMIC)
  - dielectric resonator

Dielectric Resonator Filters

- Dimensions scale by $\varepsilon^{-1/2}$
- Q decreases as ε increases with Qxf ~ constant*
  - fxQ = 200,000 for $\varepsilon = 25$
  - fxQ = 5000 for $\varepsilon = 90$
- Wireless community uses coupled $\lambda/4$ lines in high ε monoblocks to achieve low loss with small size
  - Vol < 50 mm^3 @ 1.9 GHz for 3-pole filter

*Nishikawa, MuRata, 1998 IMS Symposium

Dielectric Resonator Filters

Technical Challenges

- Improved dielectric materials: $\varepsilon > 100$, Qxf > 500,000
- Linear materials and geometries
- Ability to form complex monoblocks
- Multi-mode, multi-layer techniques
- Thermal management, temperature stability
- Packaging - high isolation, integration with active circuits
- Low cost

Technical Approach

Electromagnetic Simulations of Candidate Microstructures

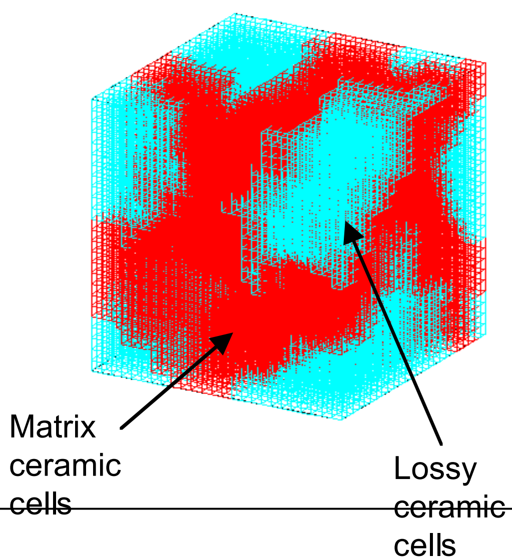
Quasi-static simulations

- Solves the equation

$$\langle (\varepsilon^* \overline{E}\,) = 0$$

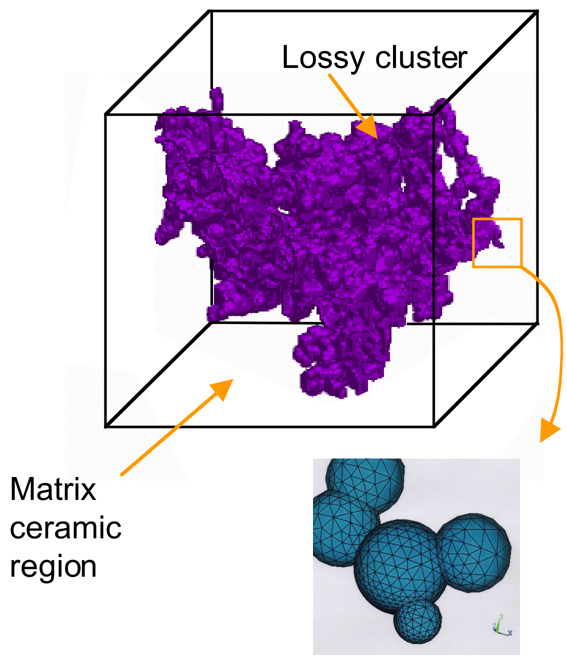
on a 3D network of cubical cells

- Non-zero frequency treated with complex permittivity ε*

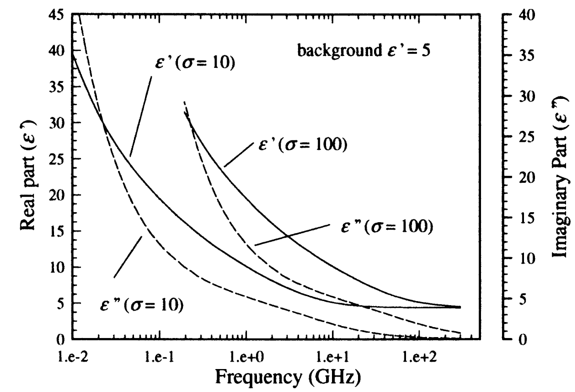


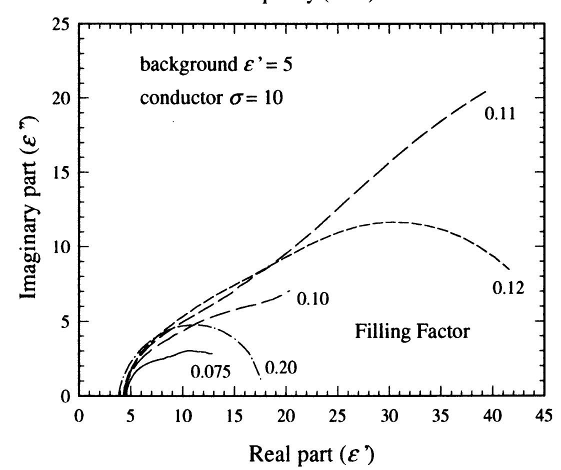
Electromagnetic simulations

- Solves full Maxwell equations in a meshed model space
- Allows treatment of lossy clusters with size approaching the material skin depth
- Can include diffusive transport



Example: Quasi-static simulations of a 2-phase system near percolation

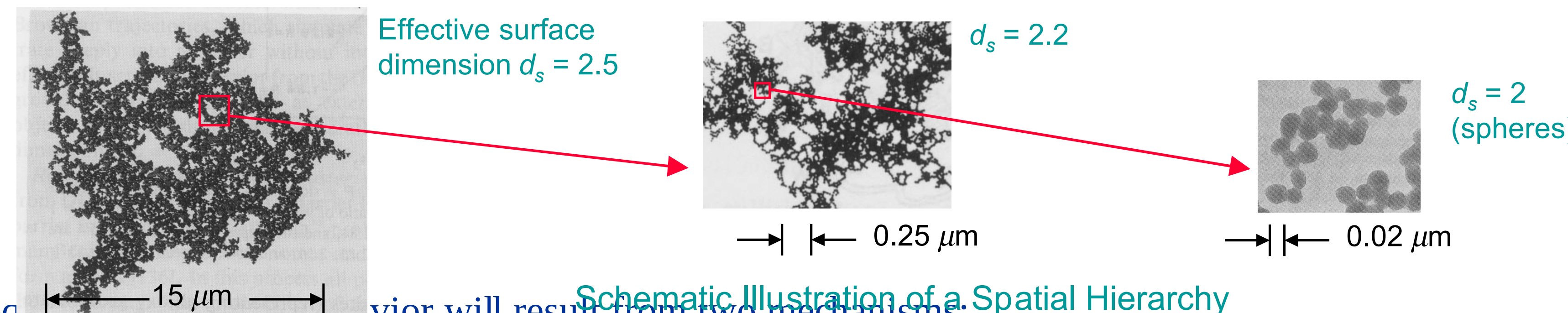




Ref: J.P. Calame, Y. Carmel, D. Gershon, and M. Rosen, "Predicting the dielectric properties of mixtures - a practical engineering approach," First World Congress on Microwave Processing, Lake Buena Vista, FL, Jan 5-9, 1997. *(Invited)*

Overview of Concept and Technical Approach

- Achieve rapid variation of dielectric permittivity with respect to frequency using <u>tailored microstructure</u> ceramic composites. Lossy material inside the matrix is arranged in <u>complex geometric patterns</u> that exhibit a spatial hierarchy of structure



Schematic Illustration of a Spatial Hierarchy

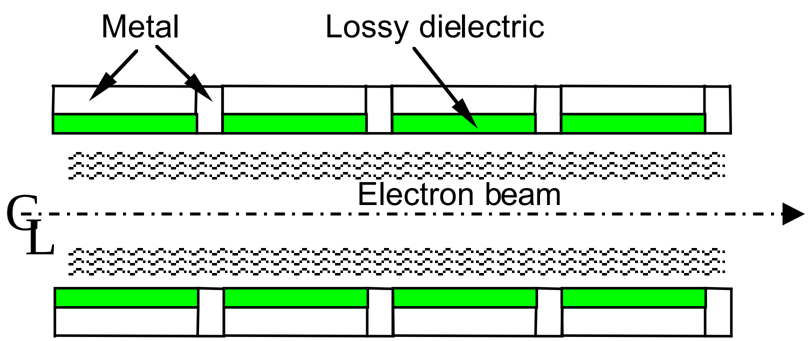
- Frequency-dependent behavior will result from two mechanisms:
  - <u>Anomalous electron diffusion</u> along the lossy structures. Diffusion distance depends on frequency, so a spatial hierarchy of structures can lead to frequency-dependent diffusion [1, 2].
  - <u>Geometrical structures functioning as a complex 3D RC-circuit</u>. Overall permittivity varies as the proportions of conventional and displacement current within the interwoven structures change with frequency [2, 3].

- Approach Summary: EM Microstructure Simulations ♦ Synthesis ♦ Characterization

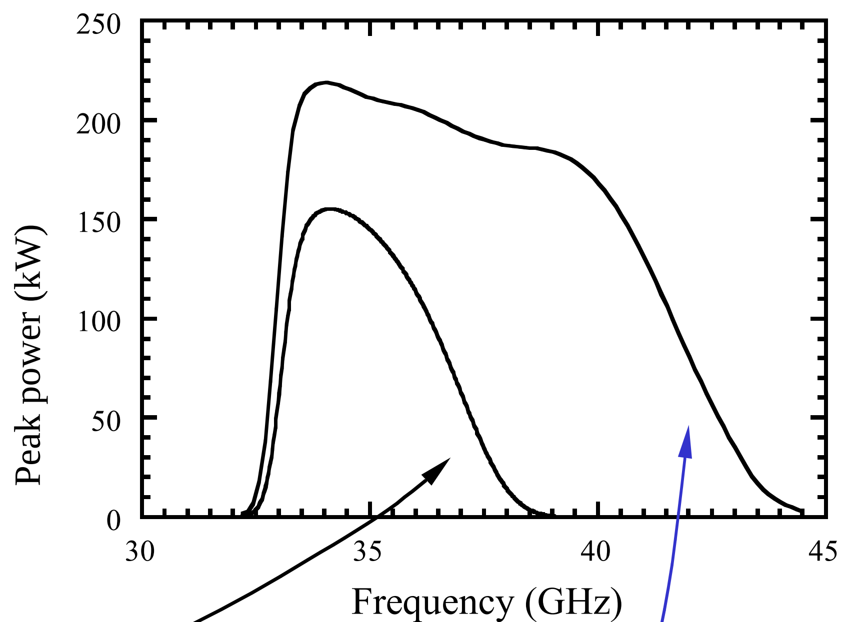
[1] D.J. Bergman and Y. Imry, "Critical Behavior of the complex dielectric constant near the percolation threshold of a heterogeneous material," Phys. Rev. Lett. 39, 1222 (1977).
[2] Y. Gefen, A. Aharony, and S. Alexander, "Anomalous diffusion on percolating clusters," Phys. Rev. Lett 50, 77 (1982).
[3] D. Wilkinson, J.S. Langer, and P. Sen, "Enhancement of the dielectric constant near a percolcation threshold, " Phys. Rev. B 28, 1081 (1983).

Example of the Impact of Tailored Frequency-Response Dielectrics

Gyro-TWT for Instrumentation Radar



Dielectric-Loaded Interaction Circuit



Computed Performance with Standard 80%AlN-20%SiC Lossy Dielectric (Dielectric Properties Constant from 30-40 GHz)

Expected Performance Capability with Lossy Dielectric Varying as $\varepsilon' \sim 1/f^{1.3}$, $\varepsilon''/\varepsilon' \sim$ Constant

(Estimated from growth rate calculations)

- 2.6↔ projected increase in bandwidth due to improved synchronism between EM fields and the beam
- 40% projected increase in power due to better suppression of oscillations

Summary/Conclusions

- New systems concepts are placing increasing demands on both active and passive component technology
- Particularly stressing for passive components are the demands on size, bandwidth, linearity and cost
- New materials concepts can be an important tool in addressing these needs
- Efficient progress will require tightly-coupled, innovative device and materials programs supported by a strong CAD effort